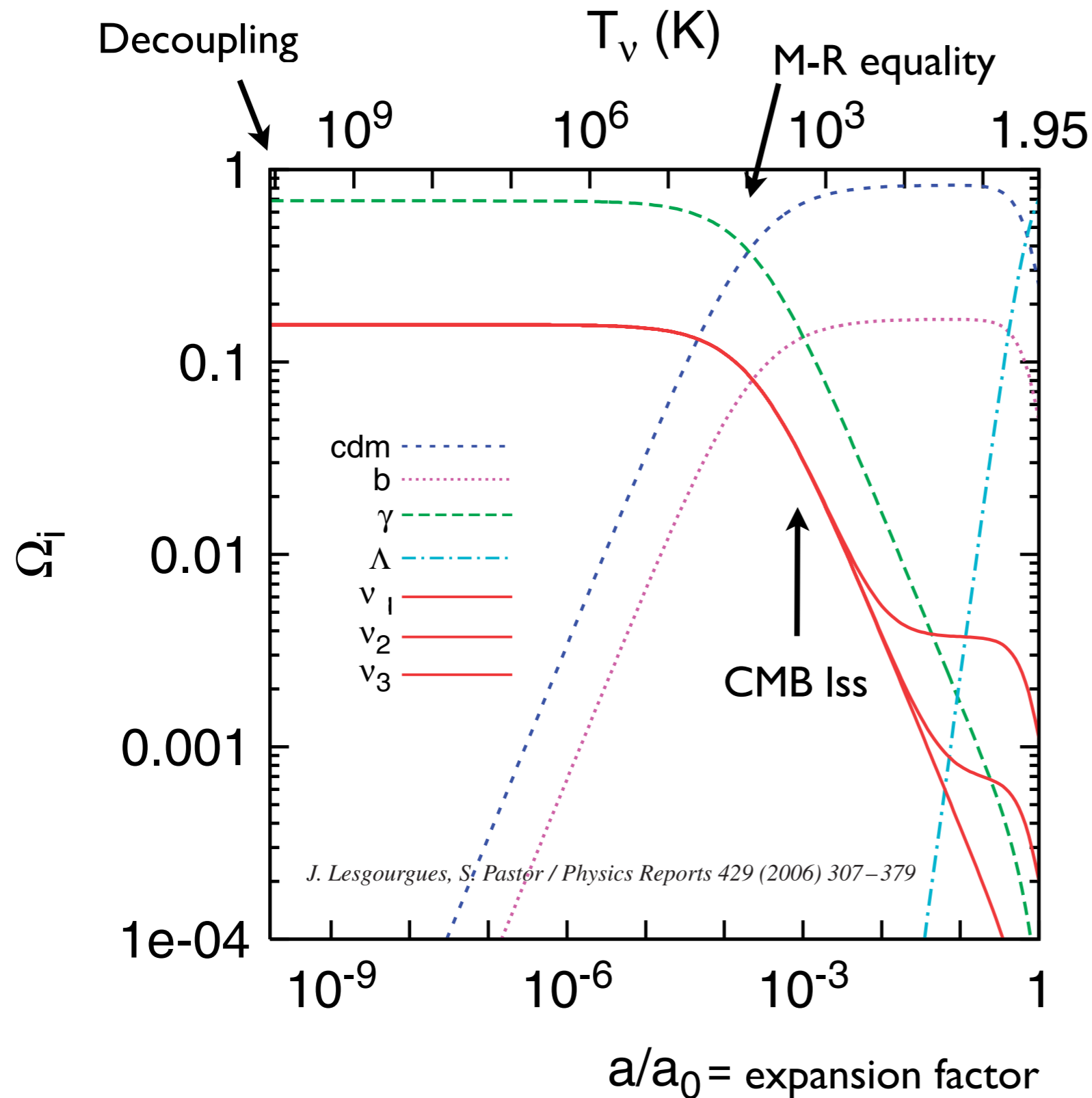# Neutrinos in LSS

Pat McDonald
(Lawrence Berkeley Lab)

Outline

- The story of neutrinos and Large Scale Structure is basically about the sum of neutrino masses (where LSS means ~tracers of large scale density fluctuations other than the CMB)

- Currently, Baryonic Acoustic Oscillation (BAO) distance measurements are important, probing the effect of neutrino mass on the background evolution.

- In the future, measurements of the suppression of structure formation by neutrino free streaming will dominate (measured by redshift space distortions and gravitational lensing).

- All in the context of critical CMB constraints.

Densities vs. time

T$_\nu$ (K)

Decoupling

M-R equality

10^9 10^6 10^3 1.95

Ω_i

cdm ------
b ·········
γ ------
Λ —·—·
ν_1 ——
ν_2 ——
ν_3 ——

CMB lss

J. Lesgourgues, S. Pastor / Physics Reports 429 (2006) 307–379

a/a$_0$ = expansion factor

$$\rho_\nu^{\rm nr} = m_\nu n_\nu$$

$$z_{\rm nr} \sim 94 \, (m_\nu/0.057 \, {\rm eV})$$

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = 0.00125 \left(\frac{m_\nu}{0.057{\rm eV}}\right) \left(\frac{h}{0.7}\right)^{-2}$$
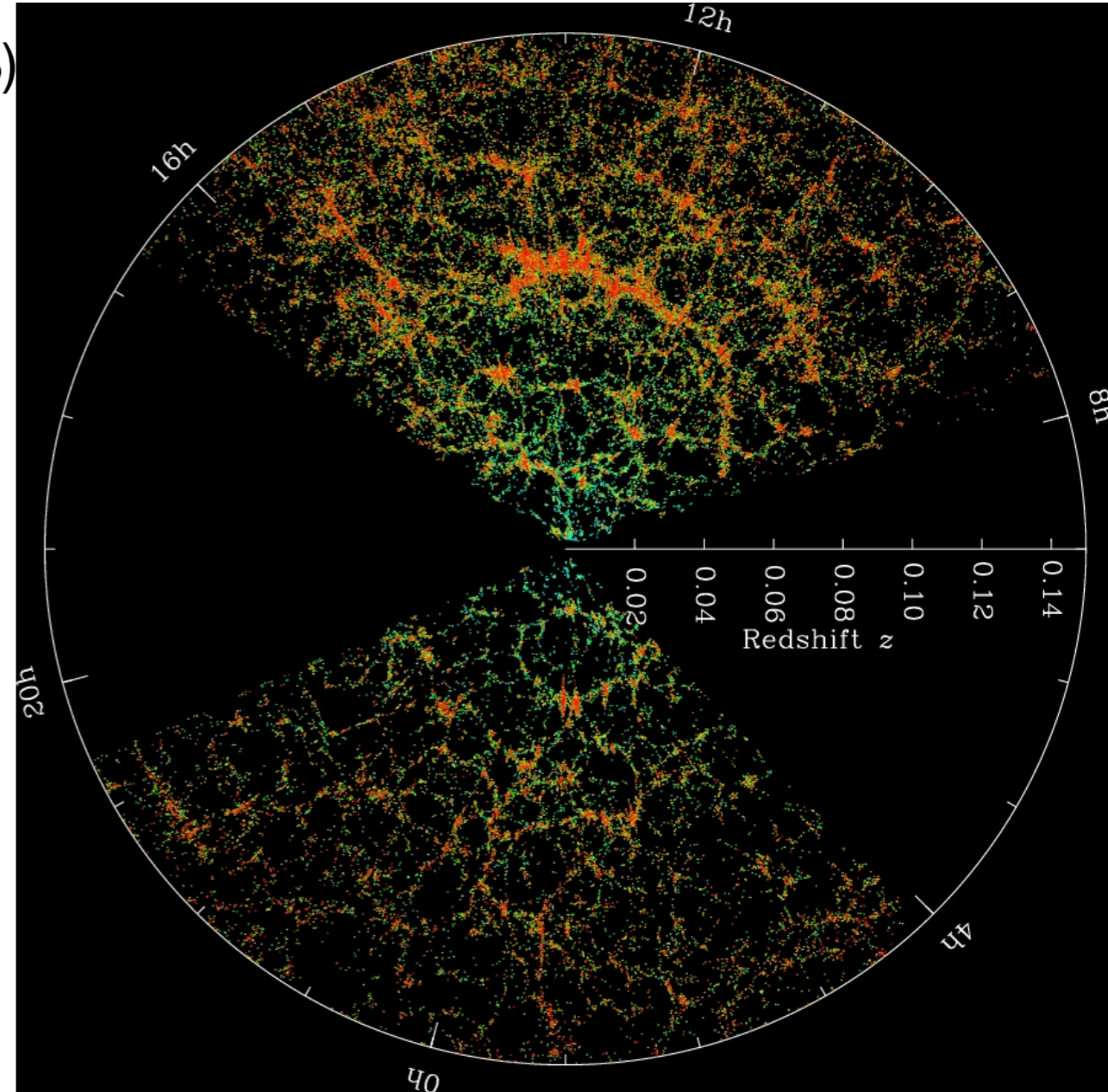
>0.4% of density today

Sum of masses vs. hierarchy

- **Key fact:** Late time clustering basically only measures the sum of neutrino masses.
- Minimum sum of masses:
  - **-**normal: 59 meV
  - **-**inverted: 100 meV
- LSS might be able to identify a minimal mass normal hierarchy.
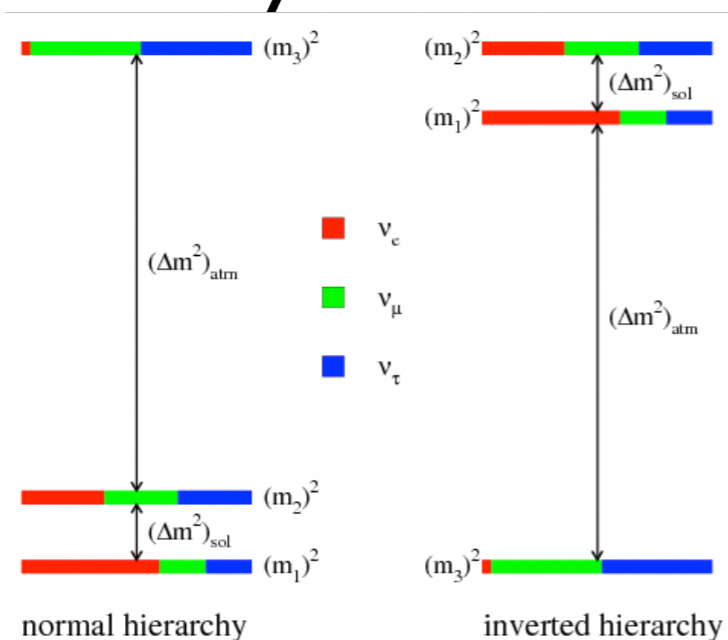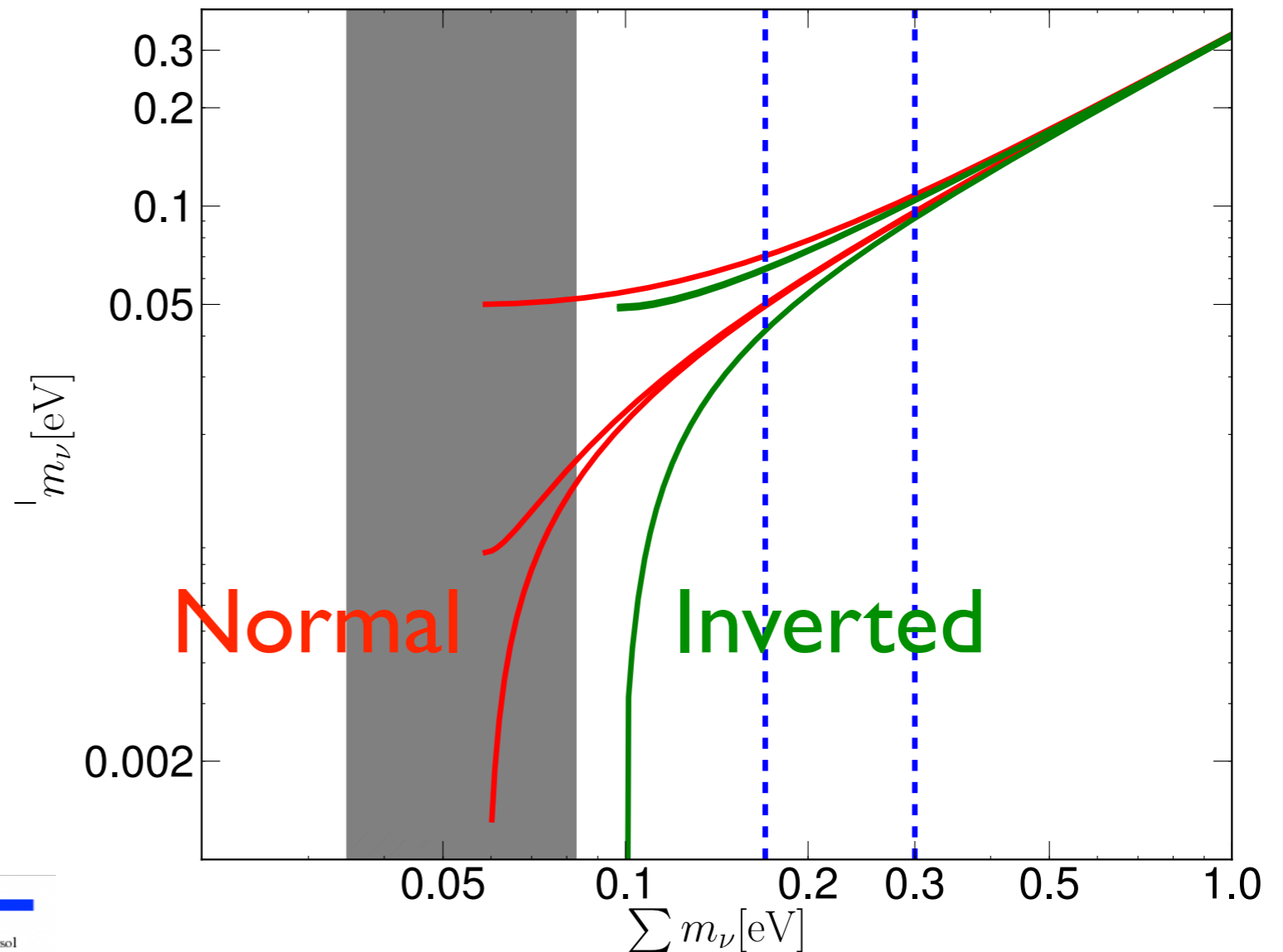
LSS basics

Density fluctuations relative to mean:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

Power spectrum: $\quad P(k) \propto \left\langle |\delta_{\mathbf{k}}|^2 \right\rangle \propto \mathrm{FT}\left[\langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle\right]$
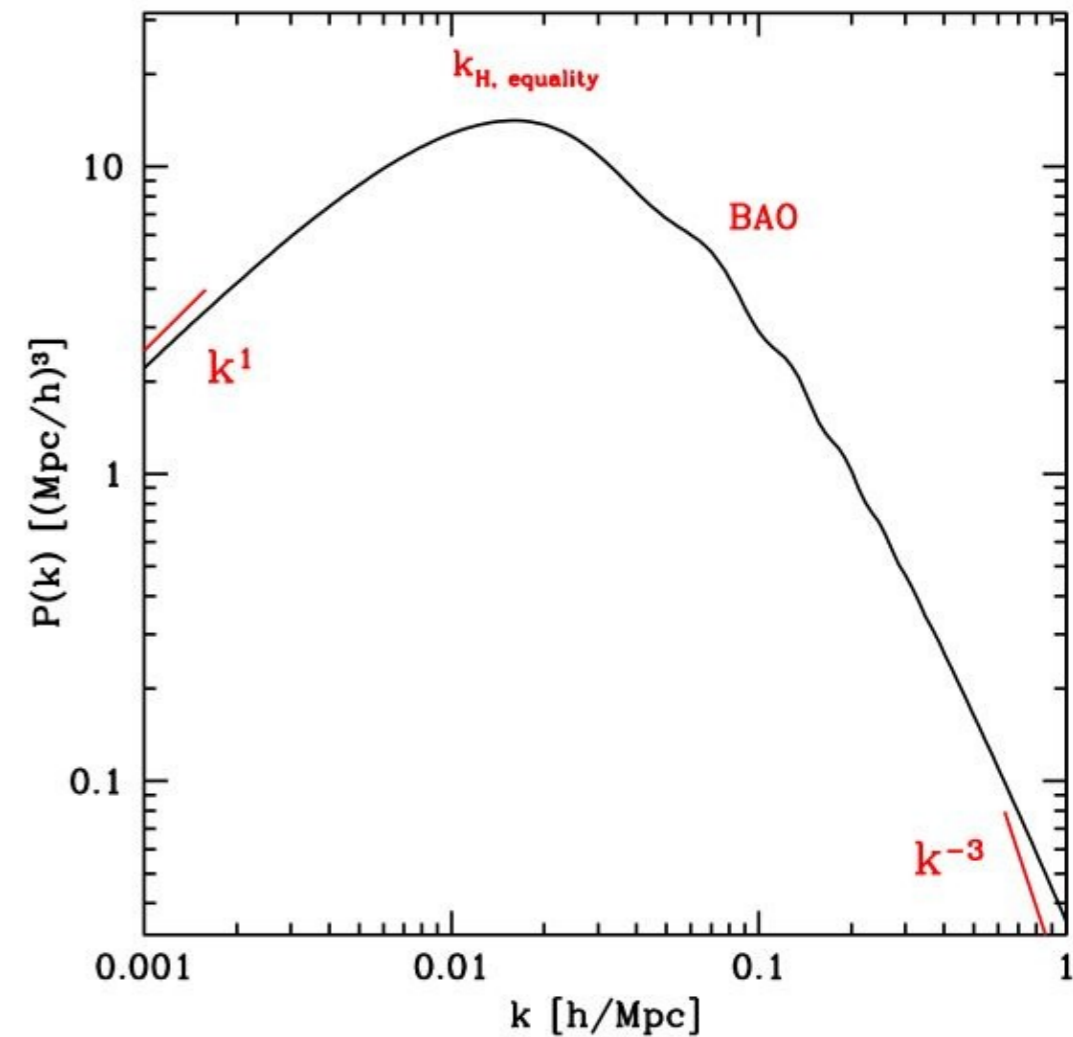
Correlation funct

0.3

0.2

LSS Basics

Initial fluctuations from inflation:

$$P_{\mathrm{inflation}}(k) = A \left(\frac{k}{k_\star} \right)^{n_{\mathrm{s}} + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_\star}\right) + \ldots}$$

Linear evolution: $\delta_i = T_i(k, z)\delta_0$

(CAMB, CLASS)

Large scale observables, perturbative bias: $\delta_g = b_g\delta + \epsilon_g + \ldots$

(infinite papers including McDonald & Roy 2009)

Non-linearity disconnects small scales from initial conditions / background Universe

Barion Acoustic Oscillations
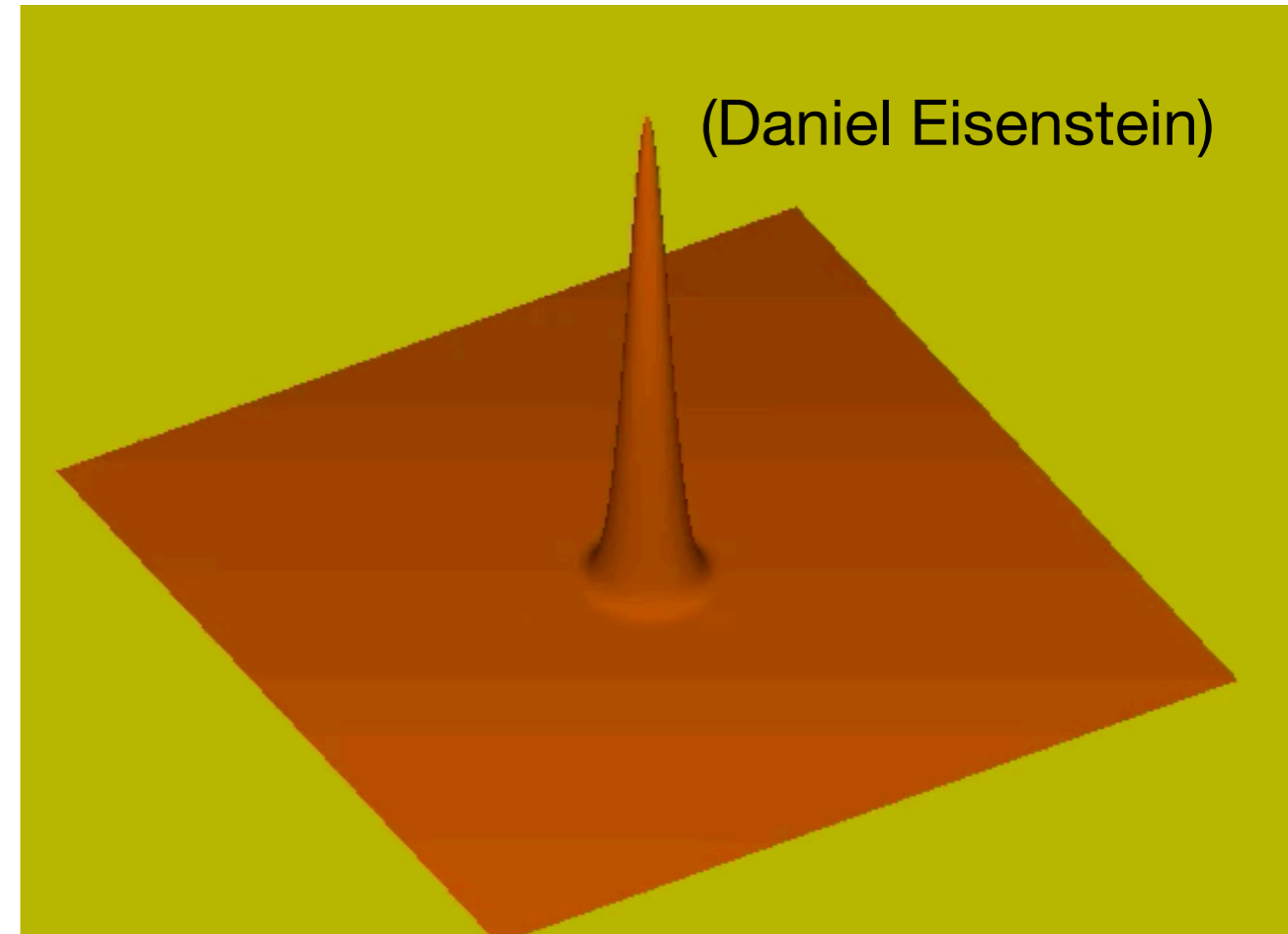
(Daniel Eisenstein)

Sound speed:

$$c_s^2 = \frac{\partial p}{\partial \rho} = \frac{c^2}{3} \left(1 + \frac{3\rho_b}{4\rho_\gamma} \right)^{-1}$$

Sound horizon:
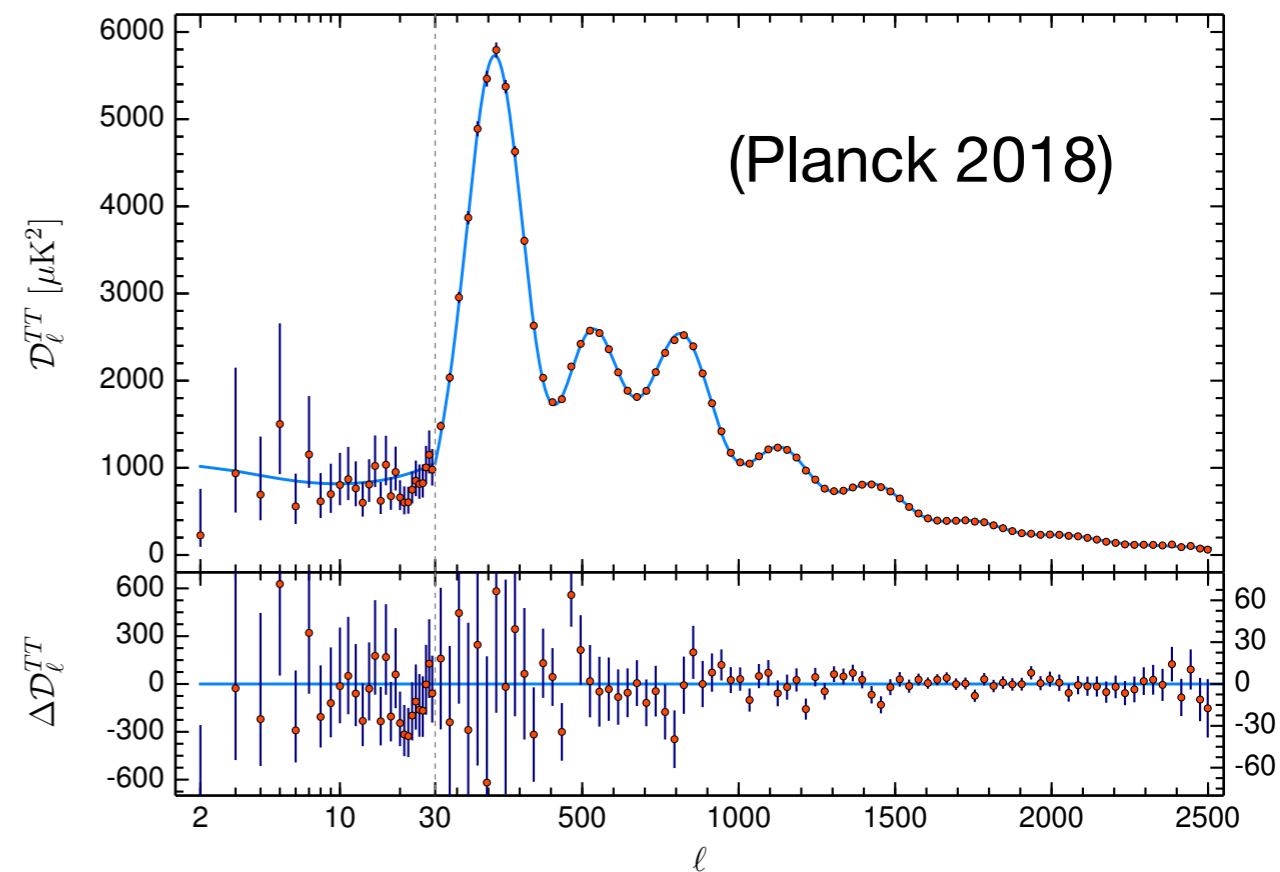
$$r_s(z_\star) = \int_{z_\star}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

(Planck 2018)

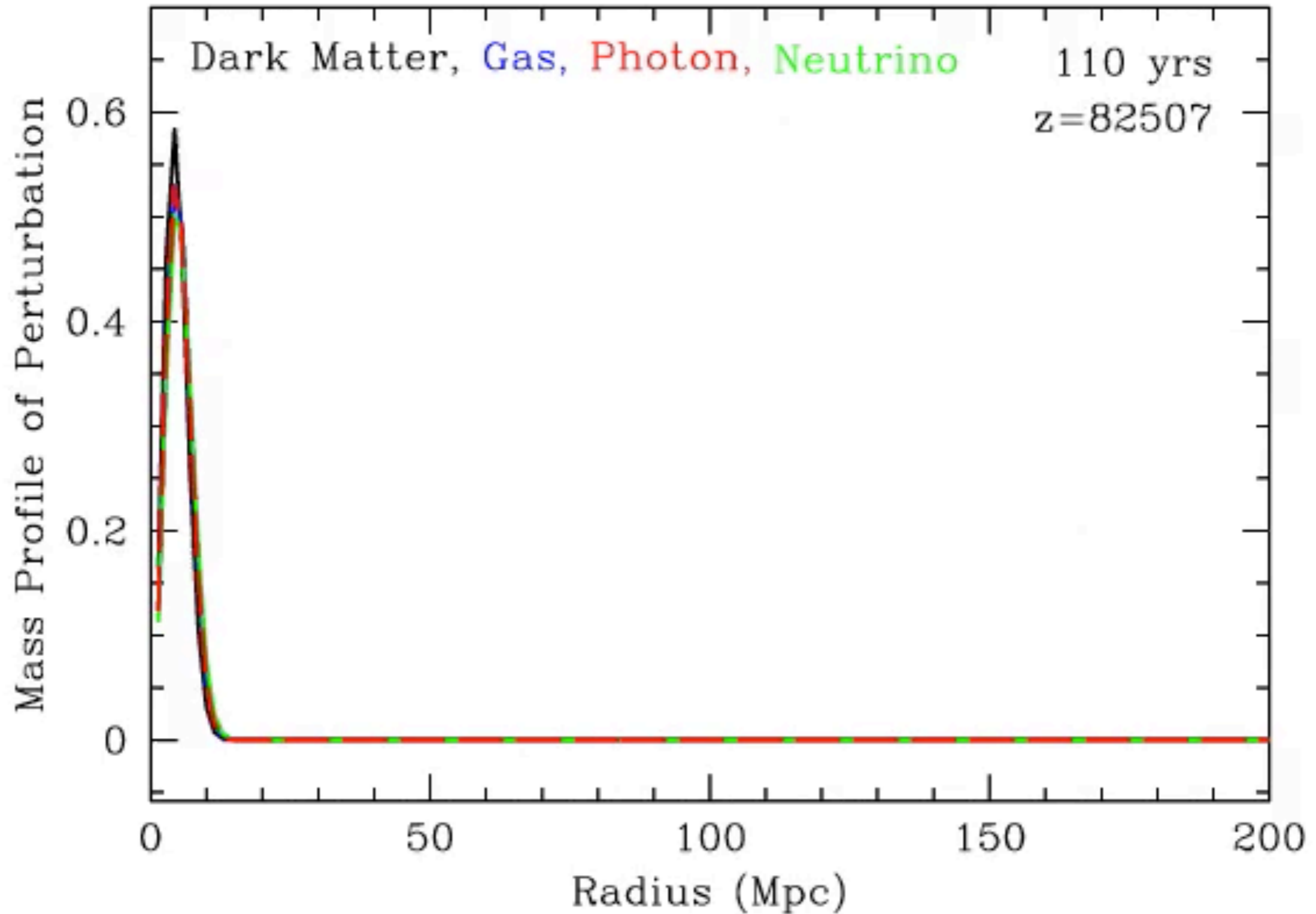CMB fixes standard ruler:

$$H^2(\text{high } z) \propto \rho_\gamma(z) + \rho_c(z) + \rho_b(z) + \rho_{\nu \sim \text{massless}}(z)$$

Dark Matter, Gas, Photon, Neutrino   110 yrs
                                             z=82507

Fluctuations are linear, so the random field result is a superposition of these solutions.

BAO

Planck 2018: $r_{\mathrm{drag}} = 147.18 \pm 0.29 \ \mathrm{Mpc}$

$$\Delta v_{BAO} = \frac{r_s}{1+z} H(z)$$

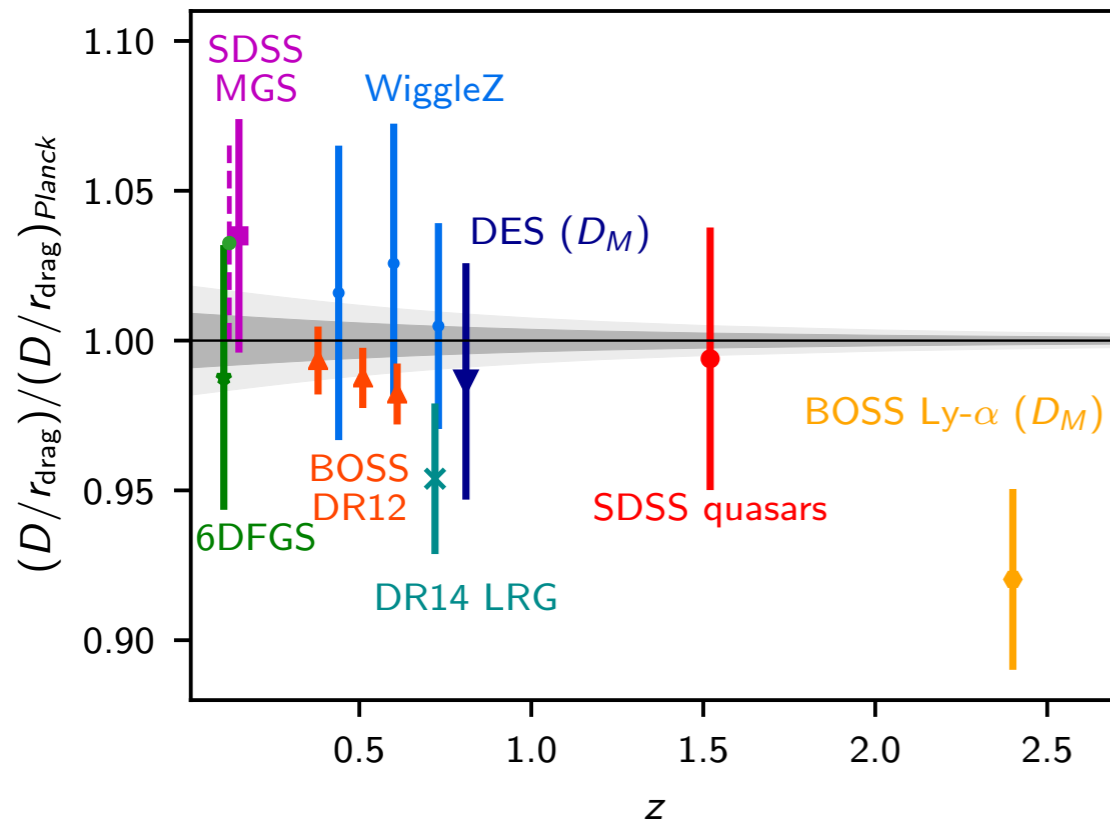$$\Delta \theta_{BAO} = \frac{r_s}{1+z} \frac{1}{D_A(z)}$$

Observer
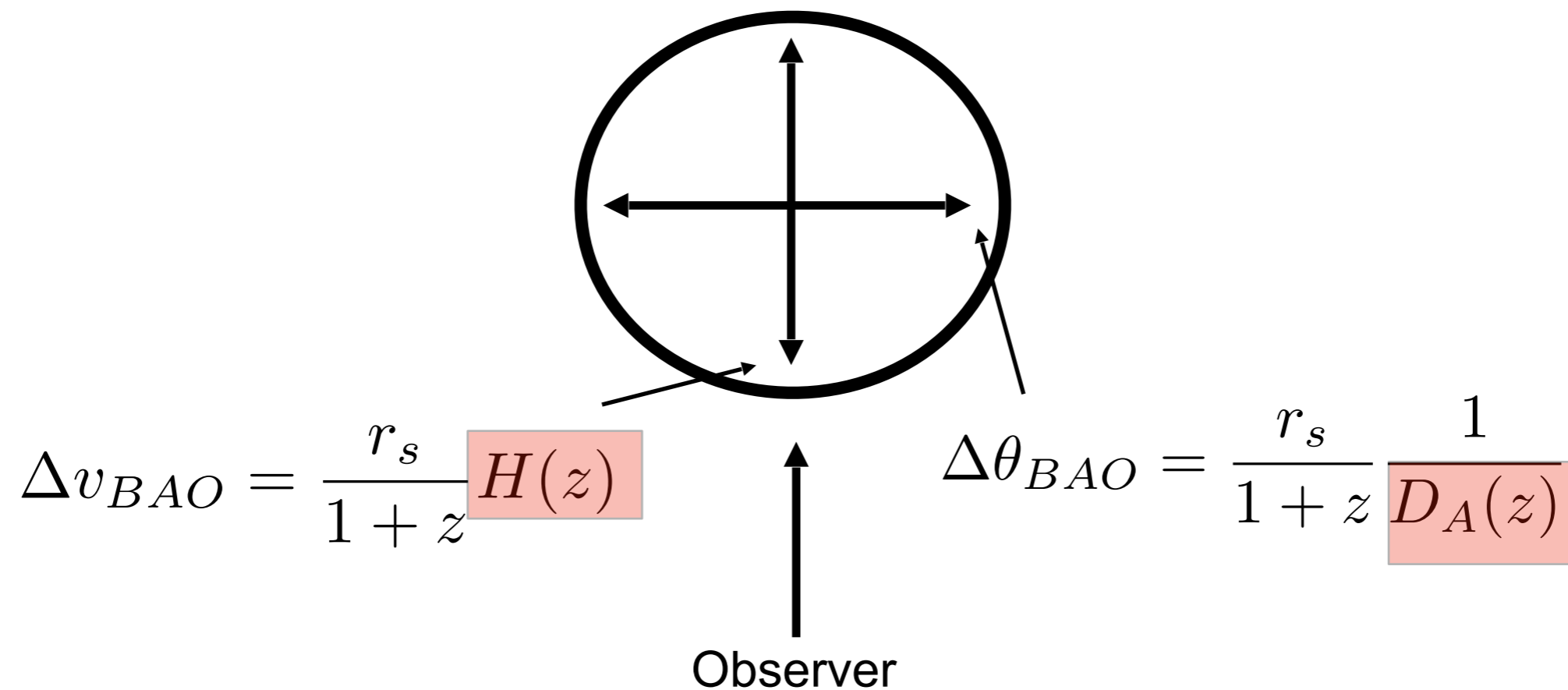
BAO and neutrinos

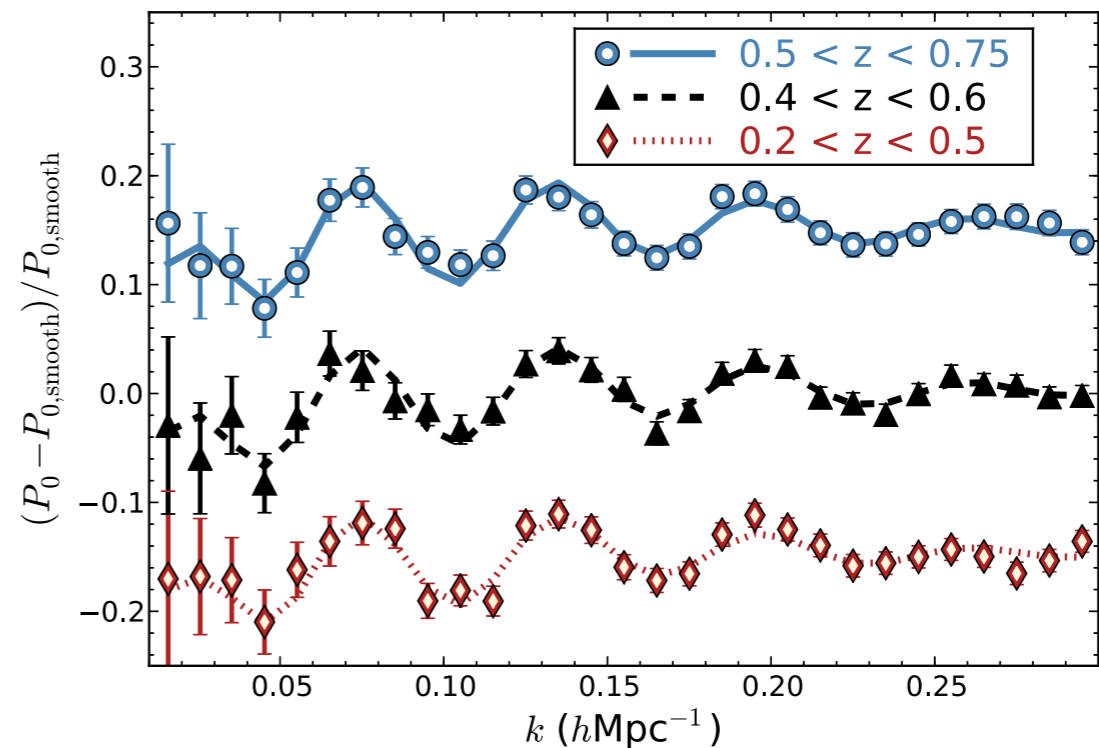$$D_A^{\text{flat}}(z) = (1+z)^{-1} \int_0^z dz' \frac{c}{H(z')}$$

Integral over H(z) to CMB
precisely measured

$$H_{\text{flat}}^2(z) \propto \rho_\gamma(z) + \rho_c(z) + \rho_b(z) + \boxed{\rho_\Lambda + \rho_\nu(z)}$$

(Planck 2018 compilation, arXiv:1807.06209)
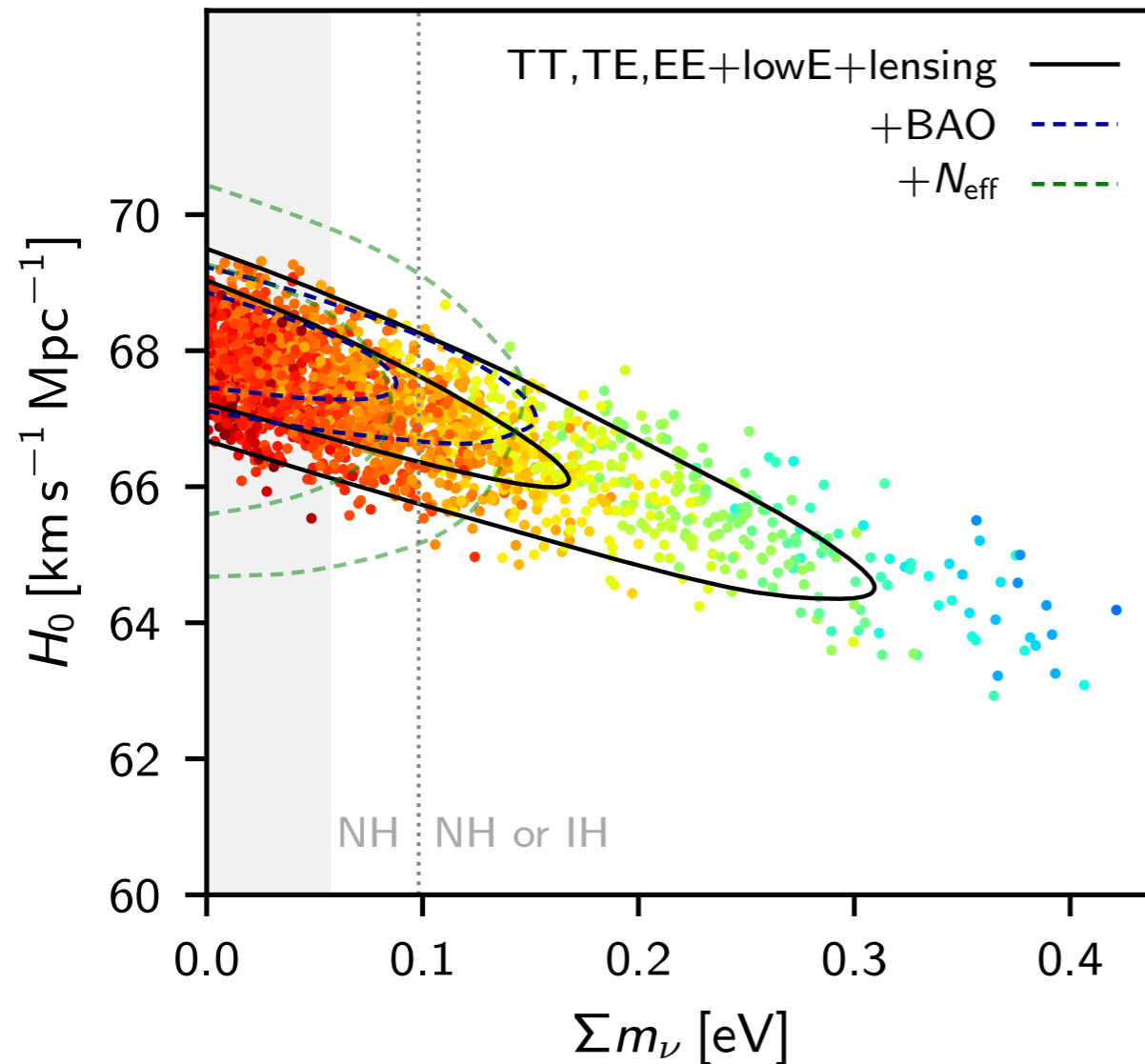
(BOSS 2017, Alam et al., Beutler et al.)

Current constraints

(Planck 2018, arXiv:1807.06209)

$\Sigma m_\nu < 120 \text{ meV } (95\%)$

Choudhury & Choubey (2018)
Planck 2015+BOSS

Model: $\Lambda CDM + \sum m_\nu$	
Dataset	$\sum m_\nu$ (95% C.L.)
TTTEEE + BAO + $\tau 0p055$	$< 0.124\,\text{eV}$
TTTEEE + BAO + FS + $\tau 0p055$	$< 0.133\,\text{eV}$

Future: DESI, etc.

0.6 million Ly-A QSOs

+1.4 million QSOs

23 million ELGs

4 million LRGs

r=5.0 Gpc
r=4.0 Gpc/h
r=3.0 Gpc/h
r=2.0 Gpc/h
r=1.0 Gpc/h
r=0.5 Gpc/h

z=4
z=3
z=2
z=1.5
z=1
z=0.7
z=0.5
z=0.2
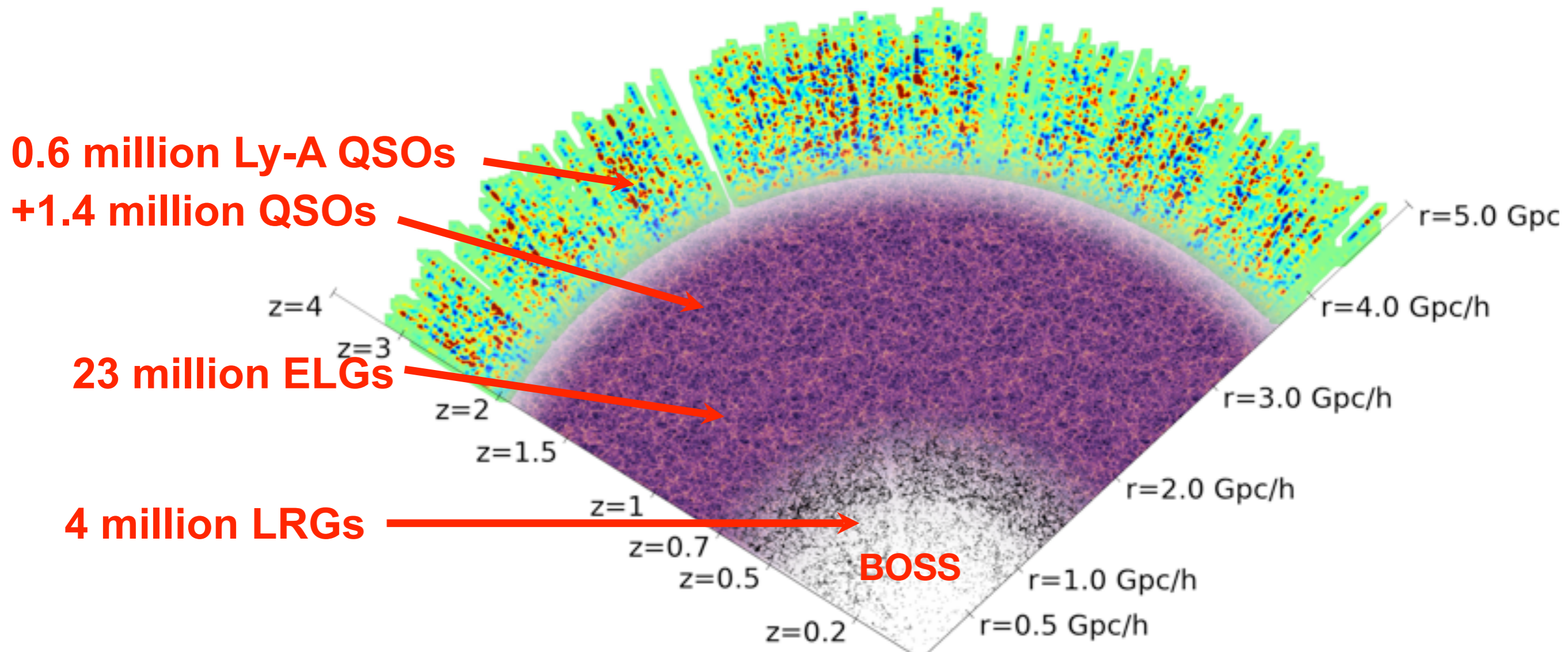
BOSS

Planck + DESI BAO rms predicted neutrino mass error 79 meV (vs. 86 meV for BOSS)

Neutrino suppression of power

$$v_{\rm rms} \simeq 3173\,(1{+}z)\,(0.057\ {\rm eV}/m_\nu)\ {\rm km\ s}^{-1}$$

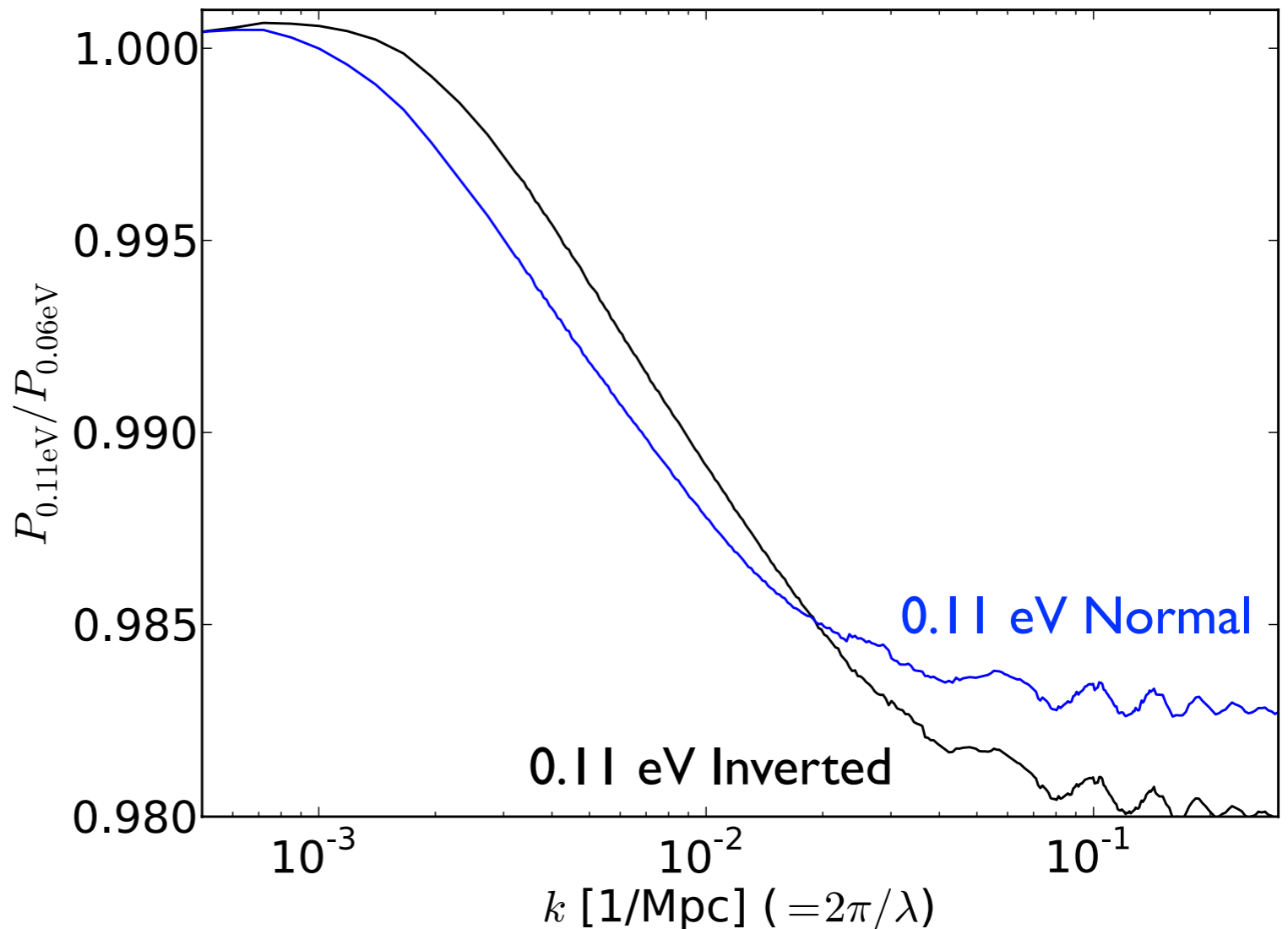- Only at z~100 does a 50 meV neutrino finally become non-relativistic.

- Contribute to the subsequent background evolution as if they were dark matter.

- Don't cluster except on very large scales.

- Mass perturbations are "underweight" and don't grow as fast as they would for pure CDM.

$$P(k) \propto \left\langle |\delta_{\bf k}|^2 \right\rangle \propto {\rm FT}\left[\left\langle \delta({\bf x})\delta({\bf x}+{\bf r})\right\rangle\right]$$

Redshift space anisotropy

$$\frac{c \, \Delta\lambda}{\lambda} \simeq \frac{H(z)}{1+z}\Delta x_{\parallel} + \Delta v_{\parallel} \longleftarrow \text{ peculiar velocity}$$

observed redshift   radial comoving separation

$$\delta_g = (b_g + \boxed{f\mu^2})\delta_{cb} + \epsilon_g + ...$$

$$\mu = \frac{k_{\parallel}}{k} \qquad f = \frac{d\ln\delta_{cb}}{d\ln a}$$
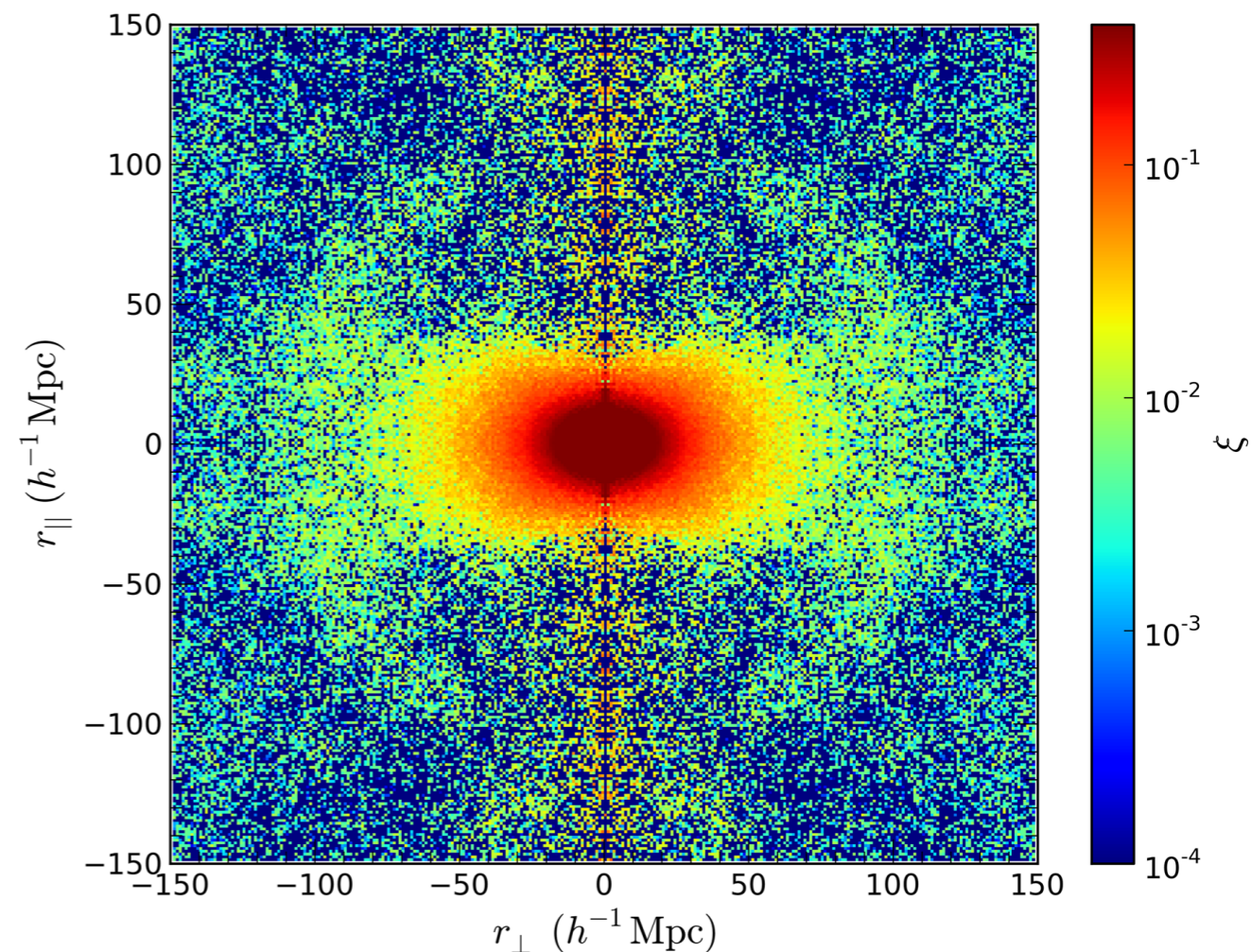
(BOSS, Samushia et al. 2014)

CMB optical depth degeneracy

Planck+DESI: $\sigma_\tau = 0.008 \;\rightarrow\; \sigma_{\Sigma m_\nu} = 29$ meV

$$\sigma_\tau = 0 \;\rightarrow\; \sigma_{\Sigma m_\nu} = 16 \text{ meV}$$

CMB measures $A_s e^{-2\tau}$ very precisely. $\quad \sigma_{\ln A_s} = 2\sigma_\tau$
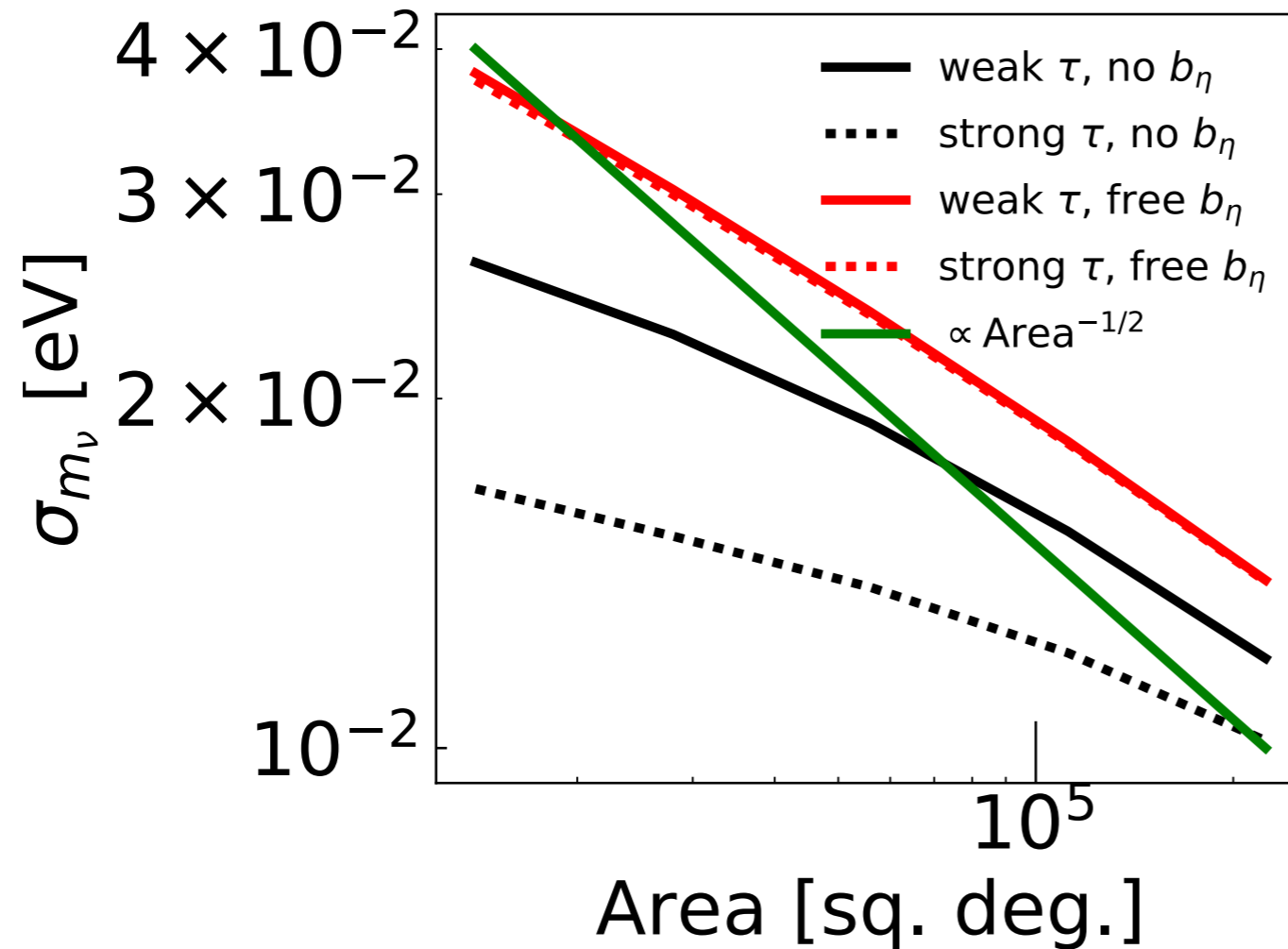

FIG. 8. Neutrino mass constraints for 90 million ~ELGs, 10 million ~LRGs per 14000 sq. deg., out to $z < 3$, vs. survey area (i.e., the galaxy survey Fisher matrix is just scaled proportional to area). Weak τ is ~0.01 prior, strong ~ 0.005, b_η means free bias on RSD term.

No wonder it is hard to measure suppression shape!

Fixed ω_b, ω_c, θ_s

(PDG summary by Lesgourgues & Verde)

Fixed $\omega_{cb\nu}$, ω_b, Ω_Λ

$P(k)/P(k)(\Sigma m_\nu = 0)$

$k \ [h^{-1}\mathrm{Mpc}]$

$\Sigma m_\nu = 0.25\mathrm{eV}$
$\Sigma m_\nu = 0.5\mathrm{eV}$
$\Sigma m_\nu = 0.75\mathrm{eV}$
$\Sigma m_\nu = 1\mathrm{eV}$
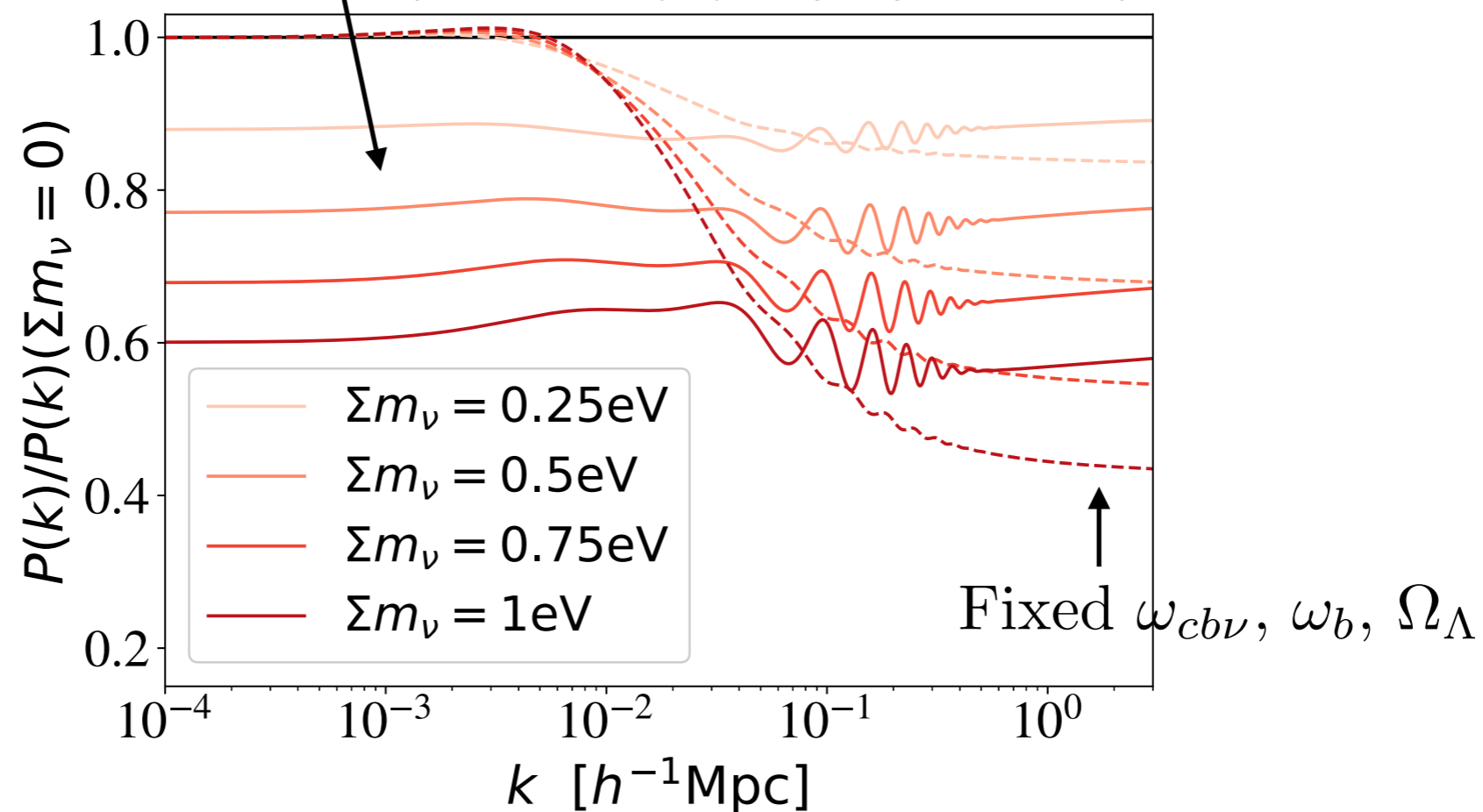
Projections

TABLE II. Projected error on Σm_ν, in meV.

surveys	σ_τ		
	0.008	0.004	0.002
Planck+DESI BAO	78	77	77
Planck+DESI	29	20	18
CMB-S4+DESI	26	17	13
CMB-S4+DESI+LSST	23	15	11
CMB-S4+MegaMapper	23	14	11
CMB-S4+LSST+MegaMapper	21	13	9.9

DESI following arXiv:1611.00036, 2020-2025+

CMB-S4 following arXiv:1610.02743, ~2029+   (S3 Simons Observatory)

LSST following Schaan et al. (2017), 2022-2032

MegaMapper: arXiv:1907.11171, 2029?? (100m galaxies 2<z<5)

Fisher matrix calculations similar to Font-Ribera et al. (2014)

Euclid would be like somewhat more DESI and somewhat more LSST

Optical depth improvements?

- CMB measurement comes from low-l polarization, hard to do from ground.

- CLASS is a ground-based experiment aimed at this, which is running and hopes to achieve better than 0.004 (Watts et al. 2018)

- BFORE balloon hopes to do something similar flying in 2021 (Bryan et al. 2018)

- LiteBIRD satellite could achieve cosmic variance limit ~0.002, launching in ~2028 (see also COrE, PICO)

Dark Radiation

current Planck: $N_{\nu,\mathrm{eff}} = 2.99 \pm 0.17$

surveys	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck+DESI	0.077
CMB-S4	0.036
CMB-S4+DESI	0.030

Extra Parameters

Projected error on Σm_ν marginalized over other parameters, for CMB-S4+DESI.

	σ_τ		
marginalized	0.008	0.004	0.002
—	26	17	13
$N_{\nu,\mathrm{eff}}$	29	17	14
β_s	27	17	13
Ω_k	40	24	20
$w(z)$	52	40	37

$$\beta_s \equiv d^3 \ln P / d \ln k^3$$

Summary

- Current constraints come from Planck+BAO

$$\Sigma m_\nu < 120 \ \mathrm{meV} \ (95\%)$$

- Future constraints ~20 meV rms will come from free streaming suppression of power, through RSD and/or lensing, with the achievable level driven by the CMB optical depth measurement, because they are driven by late time power normalization, not power spectrum shape.

Annoyingly non-simple maximum k

- Wanted to somewhat realistically account for fact that non-linearity is less of a problem at high z, and for lower bias objects.

- Cut on observable fluctuation amplitude, including z dependence and angle dependence (radial modes have higher amplitude so lower max k).

- Additionally have tracer-independent, Lagrangian displacement-inspired z and angle-dependent cut.

- Also, Seo & Eisenstein signal damping factors (e.g., makes BAO within broadband consistent with isolated BAO).
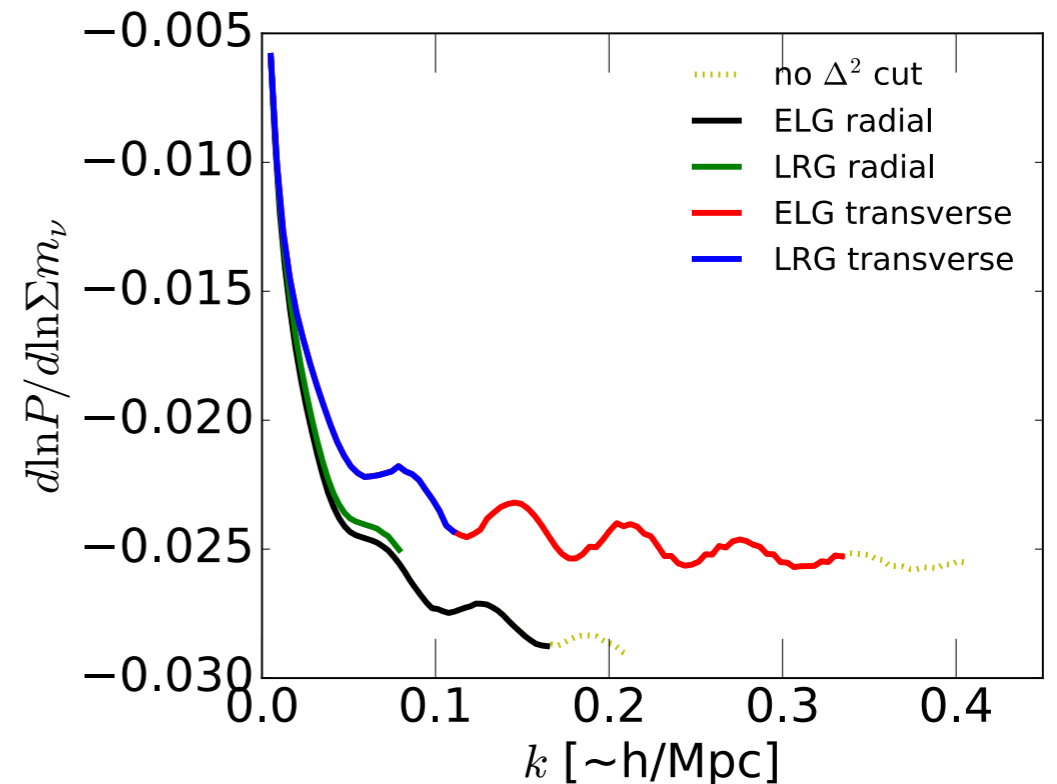

FIG. 28. Derivative of tracer power with respect to sum of neutrino masses, at $z = 1.55$ (for a case where there are some LRG-bias objects at all z). The solid lines stop at the $\Delta^2(\mathbf{k}) < 1$ cutoff that we use for Fisher calculations (which is much more stringent for high bias). The dotted lines show the object-independent maximum k, which has no impact in this case.